An Integrated Procedure for Measuring the Spatial and Temporal Resolution of Visual Displays

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ABSTRACT

Spatial and temporal resolution are two of the most fundamental characteristics of visual displays, and yet they are often incorrectly defined and specified. In order to address this problem, we have developed techniques for estimating both spatial and temporal resolution, and we have compared the resulting estimates to data obtained from perceptual tasks. The spatial resolution technique is based on a VESA standard (FPDM, Ver. 2.0), and was applied to several CRT displays. It was found that the pixel count does not adequately define display resolution when the former exceeds the bandwidth of the display device. In addition, the spatial resolution measurements were found to correlate well with perceptual assessments of the orientation of target aircraft simulated at various distances. The temporal resolution technique involved measuring the response of various displays to simple light patterns that could be flickered at up to 30 Hz. Data obtained for CRT projectors indicated that temporal artifacts obtained with these devices are due primarily to the limited frame rate of the image generator, rather than to limitations in the temporal response of the projectors. In addition, data obtained from liquid crystal on silicon (LCoS) projectors indicated that their on- and off-responses are short enough to support 60 Hz simulator frame rates, but that the hold-time used to maximize image luminance interacts with eye movements to produce temporal artifacts that can reduce the quality of the displayed imagery. The results of a perceptual test, based on the perceived separation of moving lines, were consistent with the measured temporal resolution of the two displays.

All measurement and analysis techniques described here have been implemented in a software package that is available from AFRL, Mesa, Arizona.

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14. ABSTRACT

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INTRODUCTION

The performance and utility of visual display devices are often directly related to their spatial and temporal resolution. The importance of measuring spatial resolution has long been recognized, and various methods for evaluating this characteristic have been developed (see, Keller, 1997). All of these methods involve assessing the contrast of a displayed image, but they can be distinguished on the basis of whether the assessment is performed visually or by photometric measurements. Visual assessments, such as judging when test lines are visible, are relatively easy to perform, but they are obviously dependent on perceptual factors that can differ significantly among observers. The photometric methods usually involve measuring the luminance of one or more lines, and then analyzing a calculated modulation transfer function (MTF). The MTF can be obtained either by the Fourier transform of the luminance distribution of a single line, or by directly measuring the contrast between the peaks and troughs of displayed line pairs. The major disadvantages of the transformation approach are that relatively complex computation is required, and the results are most naturally specified in terms of "bandwidths" or "cut-off frequencies", rather than directly in terms of the system characteristics relevant to a particular application. Direct measurement of line-pair contrast, on the other hand, can be used to obtain more easily interpretable estimates of the number of resolved lines (VESA, 2001).

Temporal resolution is as important as spatial resolution when specifying the capabilities of a visual display device (Parker, 1997). In fact, spatial and temporal properties are interdependent, and are often best considered in a combined spatiotemporal domain (see, e.g., Watson, Ahumada, & Farrell, 1986). Temporal resolution, like spatial resolution, can be estimated by the Fourier transform of a temporal luminance change (i.e., the temporal analog of a displayed line), or by directly measuring the contrast between the peaks and troughs of a flickering stimulus. In deciding between these approaches, the same considerations apply as were discussed in the case of spatial resolution measurements.

It has been shown that the temporal properties of a display can affect visual perception (Lindholm & Martin, 1993; Lindholm, Pierce, & Scharine, 2001; Lindholm, Scharine, & Pierce, 2003). In addition, it is well known that imagery displayed on digital devices such as LCDs show much more blurring, smearing, and color separation than does imagery displayed using fast analog devices, such as CRTs. Thus, it is particularly important to quantify the temporal properties of displays that might be used in applications, such as flight simulation, where temporal artifacts could reduce the effectiveness of the displayed imagery.

In summary, spatial and temporal resolution are two of the most fundamental characteristics of visual displays, and yet they are often overlooked or incompletely specified. In order to address this problem, we have developed an integrated procedure for measuring both spatial and temporal resolution. We have also attempted to relate the spatial-resolution measurements to human performance data on target-orientation discrimination that might be used in an air-to-air task. Finally, we have obtained data on the perceived separation of moving lines, for comparison with the temporal-resolution measurements.

SPATIAL RESOLUTION

We will describe here a relatively simple technique for measuring the spatial resolution of visual display systems. The resulting data are easily interpretable even to those not familiar with display evaluation methods. As an introduction to the technique, consider the square-wave function shown in Figure 1.

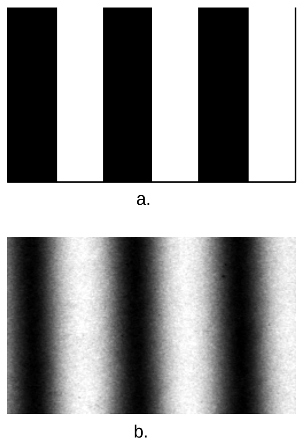

Figure 1. Ideal grille test pattern vs. displayed test pattern.

This function represents an idealized luminance distribution that corresponds, in the case of a display system, to the pixel values in the video memory of the image generator (IG). Note that a square-wave has an infinitely rapid transition from one luminance level to another, and so cannot be realized by any physical system. In order to display the luminance values represented by the square wave, those values must be interpreted by at least four components in a CRT-based display: 1) the digital-to-analog converter (DAC) of the video card, 2) the electronics that drive the CRT beam, 3) the CRT phosphor, and 4) the effective imaging system represented by the CRT lens and the display screen. Each one of these components has a limited bandwidth (i.e., capability to pass on spatial frequencies to the next device in the chain). As a result, more of the higher spatial frequencies that correspond to sharp edges (such as those making up the square-wave in Figure 1a are removed at each stage. Thus, the display system is effectively a low-pass filter. The result of this filtering is shown in Figure 1b, which is an image of the square-wave pattern more nearly as it actually appears on the display screen. The blurring associated with the reduction of the higher spatial frequency content of the input square wave is evident.

Spatial Resolution Measurement

Our technique for measuring display spatial resolution is based on a VESA Standard (VESA, 2001). First a series of vertical and horizontal grille patterns is displayed (vertical patterns are used to measure horizontal resolution, and *vice versa*). One such vertical grille pattern is shown in Figure 2.

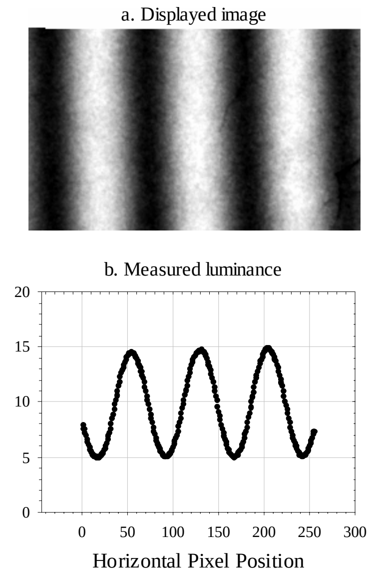

Figure 2. Grille pattern (a.) and corresponding luminance measurement (b.).

For typical displays, grille line widths between one pixel (i.e., 1-line-on/1-line-off) and 3 pixels are used. The luminance of the displayed grille pattern is then measured using a CCD camera. The Michelson contrast of each grille pattern is calculated as shown in Equation 1:

$$Cm = \frac{L\max - L\min}{L\max + L\min} \qquad (1)$$

Where Lmax and Lmin are the maximum and minimum luminance corresponding to the peaks and troughs, respectively, of the measured luminance distribution (see Figure 2b). As can be seen in the data of Figure 3, Michelson contrast typically decreases as grille width decreases for a CRT display.

The final step in estimating spatial resolution is to find a threshold grille-line width in order to estimate the number of resolved display lines. This is done by choosing a criterion contrast level (typically 0.25), and finding the corresponding grille-line width. This technique has been applied to the data of Figure 3. In that figure, a grille-line width of about 1.3 corresponds to the criterion contrast level (shown by the horizontal line). Thus, for a display system with 1600 vertical lines, the horizontal spatial resolution estimated from the data of Figure 3 would be 1600/1.3 = 1231 lines. The screen size and viewing distance can then be used to convert the number of resolved lines to arc-minutes

per line pair, or any other comparable measure. This technique is described in more detail in Geri, Winterbottom, and Pierce (2004).

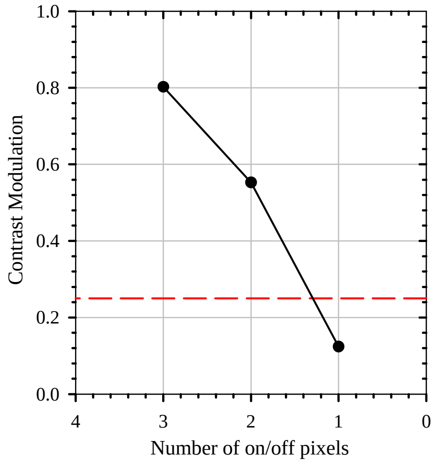

Figure 3. Contrast modulation for a CRT display.

A Comparison of the Spatial Resolution Measurements with Perceptual Data

One reason for evaluating the spatial resolution of flight simulator visual displays is to determine if those displays can adequately provide the visual cues required to perform flight-related tasks. As a first step in determining the degree to which spatial resolution measurements are related to flight-simulator performance, we have assessed the ability of observers to discriminate the orientation of target aircraft simulated at various distances on displays whose pixel count and resolution differed.

Method

Stimuli and Apparatus. Shown in Figure 4 are the F-16 models that were used as target aircraft. The targets were simulated by a PC-based image generator (IG), and displayed using CRT projectors and a rear-projection screen. In the pixel-count experiment, 1280 × 1024 or 2048 × 1536 pixel counts were used. In the spatial-resolution experiment, a 1600 × 1200 pixel count was used and spatial resolution was estimated by the measurement technique described above. Aircraft targets were simulated at distances ranging from 3281 to 12589 ft. The background image was a simulated light-blue sky whose luminance was 12 fL. The aircraft targets were black, were banked at 30°, and were displayed at one of two headings (±15°) relative to the observer, as shown in Figure 4. Observers were seated 36 in. from the display, and indicated their responses using a mouse.

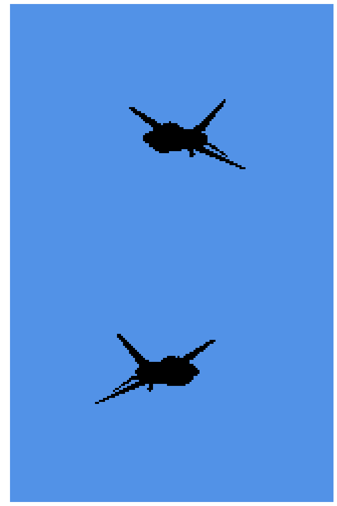

Figure 4. F-16 targets for Experiments 1 and 2.

The targets were moved in a small circle (0.06° radius) such that one revolution was completed during each 3-sec trial, while the heading direction relative to the observer was kept constant. This was done so that the target would move across several pixels during the course of the trial, thus averaging out any mismatches between the image pixels and the display pixels.

Procedure. In each trial, the observers viewed the F-16 target and responded as to whether it seemed to be headed to the right or left. The targets were presented at the center of the display, and each trial lasted for three seconds or until the observer responded. Threshold recognition distances were obtained by fitting Weibull functions to the proportion correct versus simulated-distance data, and finding the distance corresponding to a criterion proportion-correct of 0.816 (see also Winterbottom, Geri, & Pierce, 2003).

Results

Shown in Figure 5 is the relationship between target distance (i.e., size) and the proportion of correct responses on the orientation discrimination task. For these data, display pixel count was varied while resolution remained very similar (see Table 1). Shown in Figure 6 are comparable data for the case where display spatial resolution was varied while pixel count was held constant. The threshold discrimination distances are shown by the vertical lines in each figure, and are summarized in Table 1. In both figures, discrimination performance decreases as simulated distance increases.

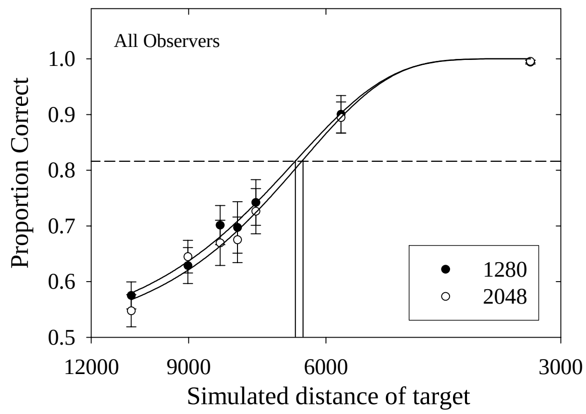

Figure 5. Target recognition performance as pixel count is varied.

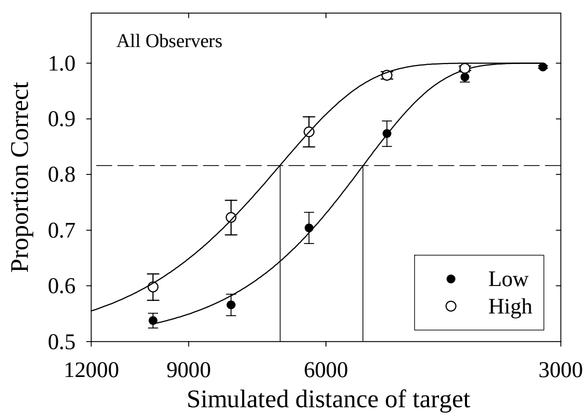

Figure 6. Target recognition performance as display spatial resolution is varied.

A within-subjects, repeated-measures ANOVA indicated that pixel count did not have a significant effect on discrimination range [$F(1,6) = 0.4$, $p > 0.05$], whereas display resolution did [$F(1,7) = 55$, $p < 0.01$].

Discussion

Although often overlooked, the importance of distinguishing pixel count (i.e., addressability) and spatial resolution is well documented (Murch & Beaton, 1988; Keller, 1997). Spatial resolution may be thought of as the ability to display fine detail at a sufficiently high contrast level. Pixel count, on the other hand, is simply the number of separate horizontal and vertical elements that are generated by the IG. The pixel count is obviously related to resolution, it is easy to specify and interpret, and it has a clear physical meaning. However, if a display device, such as a CRT, is optically defocused, for example, its resolution can be reduced, even though its pixel count has not changed.

The results shown in Figure 5 seem counterintuitive in that it might be expected that increasing the number of pixels from 1.3 million to 3.1 million would allow small objects, such as a distant simulated aircraft, to be viewed in greater detail and therefore at greater simulated distances. This is clearly not the case for the CRT projectors tested here. The resolution measurements shown in Table 1 offer an explanation. The number of resolved lines in the 1280 and 2048 pixel-count conditions are both approximately 700, which is consistent with the similarity in threshold discrimination distance for the two conditions. Likewise, the difference in resolution for the low- and high-resolution displays, in the spatial-resolution experiment, is consistent with the observed, significant difference in orientation discrimination evident in the data of Figure 6.

Table 1. Summary of measured display resolution and aircraft orientation thresholds.

Pixel Count	Resolved Pixels	Threshold Distance
1280x1024	704x651	6691
2048x1536	741x626	6785
Resolution	**Resolved Pixels**	**Threshold Distance**
Low	544x429	5431
High	1047x798	7019

TEMPORAL RESOLUTION

Several types of motion artifacts can occur when moving imagery is displayed using devices with insufficient temporal resolution. We describe next some temporal response measurements that were made on CRT and LCoS (liquid crystal on silicon) displays, and that can be related to observed motion artifacts. We also describe a perceptual test, based on the perceived separation of moving line pairs, which correlates well with the temporal resolution measurements.

Temporal Resolution Measurements

Display temporal response was measured using a photodiode-based circuit and an oscilloscope. The photodiode was directed at a flashing illuminated square generated by our test program. The program allows the size and duty cycle of the flashing square to be varied. This technique and the photodiode circuit are described in more detail by Geri and Morgan (2003).

Shown in Figure 7 are the temporal responses of both CRT and LCoS projectors to a single cycle of a 30 Hz

flashing stimulus. The CRT response is relatively fast (approx. 7.5 μsec). Each displayed pixel is illuminated and then turns off as quickly as the phosphor decay allows. This limited on-time is what gives the CRT projector its good motion quality. The LCoS display, in comparison, is much slower in its response. It has a rise time of about 5 msec, and the device is held on for the entire 16.7 msec frame. The rise time is rapid enough to provide good motion quality, but the hold-time can interact with eye movements to produce motion artifacts (see, Lindholm, *et al*., 2003).

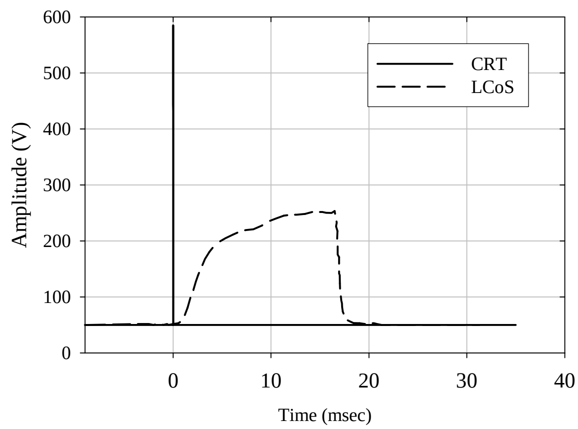

Figure 7. Temporal response for two display types.

A Comparison of the Temporal Resolution Measurements with Perceptual Data

We have developed a simple perceptual test designed to determine whether the temporal response of a display system can be correlated to the visual appearance of moving imagery. The test consists of two moving lines that cross the display screen from top to bottom, or left to right, at varying speeds. The observer is instructed to adjust the separation of the lines until the gap between them is minimized. Shown in Figure 8 are data obtained from two displays whose temporal responses differ. As discussed earlier, the CRT is a relatively fast device, and the data of Figure 8 show that the adjusted line separation is small and remains constant as line speed is increased. An LCoS display was not available for the perceptual evaluation, and so a DMD (Digital Micro-Mirror Device) display was used for comparison purposes. The DMD is similar to the LCoS display in that it is illuminated for a full frame, and in this sense has a slower temporal response than the CRT. This slower response is manifested in the data of Figure 8 as an increased line separation for all line speeds tested.

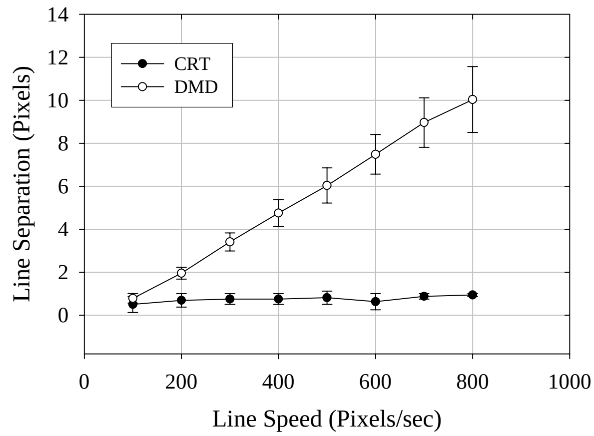

Figure 8. Observer perception of motion blur for two displays.

Discussion

The motion blur implied by the DMD data of Figure 8 is caused by the interaction of the display system and the visual system. When the eye tracks a real moving object the image of the object is relatively fixed on the retina. The eye tracks a moving object on a display screen in the same way but in this case the display provides a series of still images. As the image is displayed, the eye pans across this series of still images resulting in a smeared image on the retina. Our research shows that the magnitude of the effect is dependent on the speed at which the object moves, with the amount of smear being the distance the object moves in the time the pixel is on. This perception is not present in typical CRT displays because the on-time of any given pixel is only a few microseconds. Motion artifacts in fast devices like a CRT display could result from other factors such as frame rate and refresh rate however (Lindholm & Martin, 1993; Lindholm *et al*. 2003). In contrast, blur is evident on the DMD display because the pixels are illuminated for a much longer proportion of each frame. The presence of light for a larger proportion of the frame should not be confused, however, with the longer rise and fall times of LCD (as opposed to LCoS) devices. Longer rise and fall times will tend to blur the edges of the elongated object. This type of motion artifact is inherent in the display device itself and does not depend on an interaction with eye movements to become evident.

CONCLUSIONS

We have described here an integrated set of simple techniques for estimating the spatial and temporal resolution of visual displays. We have also provided

perceptual data that correlate well with these physical measurements of visual display performance. All measurement and analysis techniques described here have been implemented in a software package that is available from AFRL, Mesa, Arizona.

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